COMMITTEE TESTIMONY
June 19, 2012

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Induced Seismicity Potential in Energy Technologies

CQ ABSTRACT SCHEDULED WITNESSES TESTIMONY

Committee Holding Hearing:

Senate Energy and Natural Resources Committee

CQ Abstract:

Senate Energy and Natural Resources Committee (Chairman Bingaman, D-N.M.) will hold a hearing on the potential for induced seismicity from energy technologies, including carbon capture and storage, enhanced geothermal systems, production from gas shales and enhanced oil recovery.

Scheduled Witnesses:

Murray Hitzman, professor of economic geology, Colorado School of Mines, Golden, Colo.; William Leith, senior science adviser for earthquake and geologic hazards, U.S. Geological Survey; Susan Petty, president and chief technology officer, Altarock Energy Inc., Seattle, Wash.; Mark Zoback, professor, Department of Geophysics, Stanford University, Stanford, Calif.

Testimony:

Statement of Dr. Murray W. Hitzman, Charles Fogarty Professor, Economic Geology Department of Geology and Geological Engineering, Colorado School of Mines

Committee on Senate Energy and Natural Resources

June 19, 2012

Chairman Bingaman, Ranking Member Murkowski, and members of the Committee, I would like to thank you for the invitation to address you on the subject of induced seismicity potential in energy technologies. My name is Murray Hitzman. I am a professor of geology at the Colorado School of Mines in Golden, Colorado and served as the chair of the National Research Council Committee on Induced Seismicity Potential in Energy Technologies. The Research Council is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology. I would like to thank the Committee for the invitation to address it on the subject of induced seismicity potential in energy technologies.

Although the vast majority of earthquakes that occur in the world each year have natural causes, some of these earthquakes and a number of lesser magnitude seismic events are related to human activities and are called ``induced seismic events`` or ``induced earthquakes.``

Induced seismic activity has been attributed to a range of human activities including the impoundment of large reservoirs behind dams, controlled explosions related to mining or construction, and underground nuclear tests. Energy technologies that involve injection or withdrawal of fluids from the subsurface can also create induced seismic events that can be measured and felt.

Since the 1920s we have recognized that pumping fluids into or out of the Earth has the potential to cause seismic events that can be felt. Only a very small fraction of injection and extraction activities at hundreds of thousands of energy development sites in the United States have induced seismicity at levels that are noticeable to the public. However, seismic events caused by or likely related to energy development have been measured and felt in Alabama, Arkansas, California, Colorado, Illinois, Louisiana, Mississippi, Nebraska, Nevada, New Mexico, Ohio, Oklahoma, and Texas. Although none of these events resulted in loss of life or significant structural damage, their effects were felt by local residents, some of whom also experienced minor property damage. Particularly in areas where natural seismic activity is uncommon and energy development is ongoing, these induced seismic events, though small in scale, can be disturbing to the public and raise concern about increased seismic activity and its potential consequences.

Anticipating public concern about the potential for induced seismicity related to energy development, the Chairman of this Committee, Senator Bingaman, requested that the Department of Energy conduct a study of this issue through the National Research Council. The Chairman requested that this study examine the scale, scope, and consequences of seismicity induced during the injection of fluids related to energy production. The energy technologies to be considered included geothermal energy development, oil and gas production, including enhanced oil recovery and shale gas, and carbon capture and storage or CCS. The study was also to identify gaps in knowledge and research needed to advance the understanding of induced seismicity; to identify gaps in induced seismic hazard assessment methodologies and the research needed to close those gaps; and to assess options for interim steps toward best practices with regard to energy development and induced seismicity potential. The National Research Council (NRC) released the report Induced Seismicity Potential in Energy Technologies on June 15.

The committee that wrote this NRC report consisted of eleven experts in various aspects of seismicity and energy technologies from academia and industry. The committee examined peer-reviewed literature, documents produced by federal and state agencies, online databases and resources, and information requested from and submitted by external sources. We heard from government and industry representatives. We also talked with members of the public familiar with the world`s largest geothermal operation at The Geysers at a public meeting in Berkeley, California. We also spoke to people familiar with shale gas development, enhanced oil recovery, waste water disposal from energy development, and CCS at meetings in Dallas, Texas and Irvine, California. Meetings were also held in Washington, D.C. and Denver, Colorado to explore induced seismicity in theory and in practice.

This study took place during a period in which a number of small, felt seismic events occurred that were likely related to fluid injection for energy development. Because of their recent occurrence, peer-reviewed publications about most of these events were generally not available. However, knowing that these events and information about them would be anticipated in this report, the committee attempted to identify and seek information from as many sources as possible to gain a sense of the common factual points involved in each instance, as well as the remaining, unanswered questions about these cases. Through this process, the committee has engaged scientists and engineers from academia, industry, and government because each has credible information to add to better understanding of induced seismicity.

The committee found that induced seismicity associated with fluid injection or withdrawal associated with energy development is caused in most cases by change in pore fluid pressure and/or change in stress in the subsurface in the presence of faults with specific properties and orientations and a critical state of stress in the rocks. The factor that appears to have the most direct consequence in regard to induced seismicity is the net fluid balance or put more simply, the total balance of fluid introduced into or removed from the subsurface. Additional factors may also influence the way fluids affect the subsurface. The committee concluded that while the general mechanisms that create induced seismic events are well understood, we are currently unable to accurately predict the magnitude or occurrence of such events due to the lack of comprehensive data on complex natural rock systems and the lack of validated predictive models.

The committee found that the largest induced seismic events associated with energy projects reported in the technical literature are associated with projects that did not balance the large volumes of fluids injected into, or extracted from, the Earth. We emphasize that this is a statistical observation. It suggests, however, that the net volume of fluid that is injected and/or extracted may serve as a proxy for changes in subsurface stress conditions and pore pressure. The committee recognizes that coupled thermo-mechanical and chemo-mechanical effects may also play a role in changing subsurface stress conditions.

I will briefly discuss the potential for induced seismicity with each of the energy technologies that the committee considered, beginning with geothermal energy.

Geothermal Energy

The three different types of geothermal energy resources are: (1) ``vapor-dominated``, where primarily steam is contained in the pores or fractures of hot rock, (2) ``liquid-dominated``, where primarily hot water is contained in the rock, and (3) ``Enhanced Geothermal Systems`` (EGS), where the resource is hot, dry rock that requires engineered stimulation to allow fluid movement for commercial development. Although felt induced seismicity has been documented with all three types of geothermal resources, geothermal development usually attempts to keep a mass balance between fluid volumes produced and fluids replaced by injection to extend the longevity of the energy resource. This fluid balance helps to maintain fairly constant reservoir pressure close to the initial, pre-production value and aids in reducing the potential for induced seismicity.

Seismic monitoring at liquid-dominated geothermal fields in the western United States has demonstrated relatively few occurrences of felt induced seismicity. However, in vapor or steam dominated geothermal system at The Geysers in northern California, the large temperature difference between the injected fluid and the geothermal reservoir results in significant cooling of the hot subsurface reservoir rocks. This has resulted in a significant amount of observed induced seismicity. EGS technology is in the early stages of development. Many countries including the United States have pilot projects to test the potential for commercial production. In each case of active EGS development, at least some, generally minor levels of felt induced seismicity have been recorded.

Conventional Oil & Gas

Oil and gas extraction from a reservoir may cause induced seismic events. These events are rare relative to the large number of oil and gas fields around the world and appear to be related to decrease in pore pressure as fluid is withdrawn. Oil or gas reservoirs often reach a point when insufficient pressure exists to allow sufficient hydrocarbon recovery. Various technologies, including secondary recovery and tertiary recovery - also called enhanced oil recovery or EOR - can be used to extract some of the remaining oil and gas. Secondary recovery and EOR technologies both involve injection of fluids into the subsurface to push more of the trapped hydrocarbons out of the pore spaces in the reservoir and to maintain reservoir pore pressure. Secondary recovery often uses water injection or ``waterflooding`` and EOR technologies often inject carbon dioxide. Approximately 151,000 injection wells are currently permitted in the United States for a combination secondary recovery, EOR, and waste water disposal with only very few documented incidents where the injection caused or was likely related to felt seismic events. Secondary recovery through waterflooding has been associated with very few felt induced seismic events. Among the tens of thousands of wells used for EOR in the United States, the committee did not find any documentation in the published literature of felt induced seismicity.

Shale Gas

Shale formations can also contain hydrocarbons gas and/or oil. The extremely low permeability of these rocks has trapped the hydrocarbons and largely prevented them from migrating out of the rock. The low permeability also prevents the hydrocarbons from easily flowing into a well bore without production stimulation by the operator. These types of ``unconventional`` reservoirs are developed by drilling wells horizontally through the reservoir rock and using hydraulic fracturing techniques to create new fractures in the reservoir to allow the hydrocarbons to migrate up the well bore. This process is now commonly referred to as ``fracking.`` About 35,000 hydraulically fractured shale gas wells exist in the United States. Only one case of felt seismicity in the United States has been described in which hydraulic fracturing for shale gas development is suspected, but not confirmed. Globally only one case of felt induced seismicity at Blackpool, England has been confirmed as being caused by hydraulic fracturing for shale gas development. The very low number of felt events relative to the large number of hydraulically fractured wells for shale gas is likely due to the short duration of injection of fluids and the limited fluid volumes used in a small spatial area.

Waste Water Disposal

In addition to fluid injection directly related to energy development, injection wells drilled to dispose of waste water generated during oil and gas production, including during hydraulic fracturing, are very common in the United States. Tens of thousands of waste water disposal wells are currently active throughout the country. Although only a few induced seismic events have been linked to these disposal wells, the occurrence of these events has generated considerable public concern. Examination of these cases suggests causal links between the injection zones and previously unrecognized faults in the subsurface. In contrast to wells for EOR which are sited and drilled for precise injection into well-characterized oil and gas reservoirs, injection wells used only for the purpose of waste water disposal normally do not have a detailed geologic review performed prior to injection and the data are often not available to make such a detailed review. Thus, the location of possible nearby faults is often not a standard part of siting and drilling these disposal wells. In addition, the presence of a fault does not necessarily imply an increased potential for induced seismicity. This creates challenges for the evaluation of potential sites for disposal injection wells that will minimize the possibility for induced seismic activity.

Most waste water disposal wells typically involve injection at relatively low pressures into large porous aquifers that have high natural permeability, and are specifically targeted to accommodate large volumes of fluid. Of the well-documented cases of induced seismicity related to waste water fluid injection, many are associated with operations involving large amounts of fluid injection over significant periods of time. Thus, although a few occurrences of induced seismic activity associated with waste water injection have been documented, the majority of the hazardous and nonhazardous waste water disposal wells do not pose a hazard for induced seismicity. However, the long-term effects of any significant increases in the number of waste water disposal wells in particular areas on induced seismicity are unknown.

Carbon capture and sequestration

Carbon capture and sequestration - or CCS - is also a means of disposing of fluid in the subsurface. The committee found that the risk of induced seismicity from CCS is currently difficult to accurately assess. With only a few small-scale commercial projects overseas and several small-scale demonstration projects underway in the United States, there are few data available to evaluate the induced seismicity potential of this technology. The existing projects have involved very small injection volumes. CCS differs from other energy technologies in that it involves continuous injection of carbon dioxide fluid at high rates under pressure for long periods of time. It is purposely intended for permanent storage - meaning that there is no fluid withdrawal. Given that the potential magnitude of an induced seismic event correlates strongly with the fault rupture area, which in turn relates to the magnitude of pore pressure change and the rock volume in which it exists, the committee determined that large- scale CCS may have the potential for causing significant induced seismicity.

The committee`s findings suggest that energy projects with large net volumes of injected or extracted fluids over long periods of time, such as long-term waste water disposal wells and CCS, appear to have a higher potential for larger induced seismic events. The magnitude and intensity of possible induced events would be dependent upon the physical conditions in the subsurface state of stress in the rocks, presence of existing faults, fault properties, and pore pressure.

The committee also investigated governmental responses to induced seismic events. Responses have been undertaken by a number of federal and state agencies in a variety of ways. Four federal agencies the Environmental Protection Agency (EPA) the Bureau of Land Management (BLM), the U.S. Department of Agriculture Forest Service (USFS), and the U.S. Geological Survey (USGS) and different state agencies have regulatory oversight, research roles and/or responsibilities related to different aspects of the underground injection activities that are associated with energy technologies. Currently EPA has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act. It is important to note that the Safe Drinking Water Act does not explicitly address induced seismicity.

To date, federal and state agencies have dealt with induced seismic events with different and localized actions. These actions have been successful but have been ad hoc in nature. With the potential for increased numbers of induced seismic events due to expanding energy development, government agencies and research institutions may not have sufficient resources to address unexpected events. The committee concluded that forward-looking interagency cooperation to address potential induced seismicity is warranted. Methodologies can be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The committee determined that such assessments should be undertaken before operations begin in areas with a known history of felt seismicity and updated in response to observed, potentially induced seismicity. The committee suggested that practices that consider induced seismicity both before and during the actual operation of an energy project should be employed to develop a ``best practices`` protocol specific to each energy technology and site location. The committee`s meetings with individuals from Anderson Springs and Cobb, California, who live with induced seismicity continuously generated by geothermal energy production at The Geysers were invaluable in understanding how such a best practices protocol works.

Although induced seismic events have not resulted in loss of life or major damage in the United States, their effects have been felt locally, and they raise some concern about additional seismic activity and its consequences in areas where energy development is ongoing or planned. Further research is required to better understand and address the potential risks associated with induced seismicity.

I would like to thank the Committee for its time and interest in this subject and I look forward to questions.

Dr.William Leith, senior science advisor, U.S. Department of the Interior

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Committee: Senate Energy and Natural Resources Committee

Subject: Induced Seismicity Potential in Energy Technologies

Testimony:

Statement of Dr.William Leith, Senior Science Advisor, Earthquake and Geologic Hazards, U.S. Geological Survey, U.S. Department of The Interior

Committee on Senate Energy and Natural Resources

June 19, 2012

Chairman Bingaman, Ranking Member Murkowski, Members of the Committee, thank you for inviting the U.S. Geological Survey (USGS) to testify at this hearing on induced seismicity. My name is Bill Leith. I am the Senior Science Advisor for Earthquake and Geologic Hazards at the U.S. Geological Survey (USGS). The USGS is the science agency for the Department of the Interior (DOI). As part of its strategy to meet future energy needs, limit emissions of greenhouse gases, and safely dispose of wastewater, the United States is expanding the use of technologies that involve the injection, and in some cases the associated production, of fluid at depth. As detailed in the report released last week by the National Research Council (NRC), Induced Seismicity Potential in Energy Technologies (hereafter, NRC report), the injection and production practices employed in these technologies have, to varying degrees, the potential to introduce earthquake hazards. I would like to commend this Committee for requesting that such a study be undertaken and the Department of Energy (DOE) for funding the study. The members of the National Research Council panel who wrote the report have done an outstanding job and have made a significant and lasting contribution to the public discourse on this important issue.

The USGS is well positioned to provide solutions for challenging problems associated with meeting the Nation`s future energy needs. Various new approaches to produce oil and gas and alternative energy entail deep injection of fluid that can induce earthquakes. The cause and effect of induced earthquakes pose a number of risks that must be understood. USGS scientists, along with scientists from the National Labs and Universities funded by DOE, are already involved in studying a number of these injection projects, and we possess substantial expertise in the associated science and technology of mitigating the effects of induced earthquakes. I summarize here the research topics that the USGS can address in order to assist the Nation in meeting its future energy needs through an improved understanding of induced seismicity that leads to mitigation of the associated risks.

To put this hazard in perspective, since the beginning of 2011 the central and eastern portions of the United States have experienced a number of moderately strong earthquakes in areas of historically low earthquake hazard. These include earthquakes of magnitude (M) 4.7 in central Arkansas on February 27, 2011; M5.3 near Trinidad, Colorado on August 23, 2011; M5.8 in central Virginia also on August 23, 2011; M4.8 in southeastern Texas on October 20, 2011; M5.6 in central Oklahoma on November 6, 2011; M4.0 in Youngstown, Ohio, on December 31, 2011; and M4.8 in east Texas on May 17, 2012. Of these, only the central Virginia earthquake is unequivocally a natural tectonic earthquake. In all of the other cases, there is scientific evidence to at least raise the possibility that the earthquakes were induced by wastewater disposal or other oil- and gas-related activities. Research completed to date strongly supports the conclusion that the earthquakes in Arkansas, Colorado and Ohio were induced by wastewater injection. Investigations into the nature of the Oklahoma and Texas earthquakes are in progress.

The disposal of wastewater from oil and gas production by injection into deep geologic formations is a process that is being used more frequently in recent years. The occurrence of induced seismicity associated with wastewater disposal from natural gas production, in particular, has increased significantly since the development of technologies to facilitate production of gas from shale and tight sand formations. While there appears to be little seismic hazard associated with the hydraulic fracturing process that prepares the shale for production (hydrofracturing), the disposal of waters produced with the gas does appear to be linked to increased seismicity, as was made evident by the earthquake sequence near the Dallas-Fort Worth airport in 2008 and 2009. In addition, recent research by USGS seismologist Bill Ellsworth and colleagues has documented that M3 and larger earthquakes have significantly increased in the U.S. mid-continent since 2000, from a long-term average of 21 such earthquakes per year between 1970 and 2000, to 31 per year during 2000-2008, to 151 per year since 2008. Most of this increase in seismicity has occurred in areas of enhanced hydrocarbon production and, hence, increased disposal of production-related fluids.

Industry has been working to expand the development of unconventional geothermal resources known as Enhanced Geothermal Systems (EGS), because of their significant potential to contribute to the U.S. domestic energy mix. These geothermal resources are widespread throughout the United States and are areas of high heat flow but low permeability. To make EGS projects viable, the permeability of geologic formations must be enhanced by injecting fluid at high pressure into the low- permeability formations and inducing shear slip on pre-existing fractures. This process of permeability enhancement generally induces a large number of very small earthquakes with magnitudes less than 2 (microearthquakes). The microearthquakes provide critical information on the spatial extent and effectiveness of reservoir creation. Depending on the circumstances, however, the resulting seismicity can have serious, unintended consequences, such as project termination, if any of the induced events are sufficiently large (greater than magnitude 4) to result in surface damage or disturbance to nearby residents. As a means to address these issues, the DOE published an induced seismicity protocol in 2012, which is cited in the NRC study as ``a reasonable initial model for dealing with induced seismicity that can serve as a template for other energy technologies.``

As emphasized in the NRC report, there is a potential seismic hazard associated with geologic carbon sequestration projects that involve the injection of very large quantities of CO2 into sedimentary basins, some of which are located in or near major urban centers of the eastern and central United States. Because carbon dioxide storage requires a high porosity formation of high permeability that is capped by an impermeable seal (e.g., shale), there are two important sources of seismic risk. The first type of risk is due to the possibility of a large magnitude earthquake that causes damage to structures in the environs of the project. More importantly, there is the possibility that an induced earthquake rupture would breach the cap rock allowing the CO2 to escape. Historically, the USGS has contributed significantly toward understanding seismicity induced by liquid injection, starting with the Rocky Mountain Arsenal in the 1960`s, where it was first discovered that liquid waste disposal operations can cause earthquakes.

Between 1969 and 1973, the USGS conducted a unique experiment in earthquake control at the Rangely oil field in western Colorado. This experiment confirmed the predicted effect of fluid pressure on earthquake activity and demonstrated how earthquakes can be controlled by regulating the fluid pressure in a fault zone. The state of the science on the earthquake hazard related to deep well injection was summarized by the USGS in 1990, in a review that proposed criteria to assist in regulating well operations so as to minimize the hazard. This study was part of a co-operative agreement with EPA and was used to inform site selection and operating criteria during the development of underground injection control regulations for Class I Hazardous wells. This 1990 study is the most recent review of this topic but is likely to be superseded by the new NRC report. With support from our partners, USGS scientists are currently investigating induced seismicity associated with brine disposal operations in the Paradox Basin of Colorado and the Raton Basin coal bed methane field along the Colorado-New Mexico border. We and our partners, including the DOE, are also investigating the state of stress, heat flow, and microseismicity within geothermal reservoirs to evaluate the effectiveness of hydraulic stimulation for EGS. The combination within USGS of expertise in both energy science and earthquake science has proven particularly effective in addressing current issues.

Some of the key questions that arise in connection with fluid injection and production projects are:

-- What factors distinguish injection activities that induce earthquakes from those that do not?

-- To what extent can the occurrence of earthquakes induced by deep liquid-injection and production operations be influenced by altering operational procedures in ways that do not compromise project objectives?

-- Can deep liquid-injection operations interact with regional tectonics to influence the occurrence of natural earthquakes by, for example, causing them to occur earlier than they might have otherwise? Similarly, can induced earthquakes trigger much larger tectonic earthquakes?

-- What distribution of earthquakes (frequency of occurrence as a function of magnitude) is likely to result from a specified injection operation?

-- What is likely to be the magnitude of the largest induced earthquake from a specific injection operation?

-- What is the probability of ground motion from induced earthquakes reaching a damaging level at a particular site, and what would be the consequences (e.g., injury and/or structural damage)?

In the recent NRC report and in workshops sponsored by the DOE, , a common need has been identified for research to address the science questions posed above. The USGS, as an independent and unbiased science organization, can play a major role in studying, assessing, and providing solutions to these problems. We are already working collaboratively with DOE and U.S. Environmental Protection Agency on some of these issues, in response to the President`s establishment of the interagency hydraulic fracturing working group, as well as with the States. Although our primary research is directed at natural earthquakes and hydrogeology, we have in the past assessed the hazards associated with induced earthquakes due to mining operations, reservoir impoundment, oil and gas production and fluid injection. Thus, for many of these items, the research would mostly involve modifying existing approaches to the specialized requirements of fluid injection- and production-induced earthquakes.

Addressing these science problems will require a multidisciplinary approach that includes research in seismology, hydrology, crustal deformation, laboratory rock mechanics, in situ stress and fracture permeability, heat transport, fluid flow and other areas of study. The research activities might potentially include field-scale experiments, laboratory rock mechanics experiments, and the development and application of numerical models that simulate the effects of fluid injection operations on fracturing, fault reactivation and stress transfer, especially in low-permeability formations. Careful analyses of published case histories involving seismicity caused by fluid injection and production operations would be an important component of a comprehensive research program.

The involvement of industry is welcomed and may be essential to make progress on many of the key science questions. We see value in establishing an experimental site, or sites, in cooperation with industry and other agencies that could further the early work on induced earthquake triggering that was conducted so long ago at the Rangely field in Colorado. We note that DOE has in fact proposed a government-managed test site for EGS in its FY13 budget proposal, at which such R&D could be conducted in a carefully controlled and instrumented environment. While a comprehensive effort is needed, and is called for in the NRC`s recent report, any federal research dollars spent to minimize the risks of induced seismicity will serve multiple goals. Not only is this research relevant to shale gas development, geothermal development and carbon sequestration, but it also addresses several important gaps in our knowledge of the natural earthquake process and fault behavior.

I wish to expand on two of the findings and recommendations in the NRC report:

The first of these is what I will call the ``data gap``, for which the report recommends, ``Data related to fluid injection... should be collected by state and federal regulatory authorities in a common format and made publicly available (through a coordinating body such as the USGS).`` Currently, the data on injection volumes, rates and pressures needed to address many of the research questions above are simply lacking for many sites of induced seismicity. Permitting requirements for Underground Injection Control (UIC) wells are defined under Safe Drinking Water Act regulations, administered by the EPA and the states. Unless the potential for induced seismicity has been identified as a local risk prior to issuing a UIC permit, data collection required under these permits may not be sufficient to make confident cause-and-effect statements about injection-induced earthquakes after the fact, making it difficult to provide useful information to the regulating authorities about whether a particular disposal operation has or will have increased local earthquake risk.

Without more precise and complete data, it will be very difficult to assess the hazard potential from the tens of thousands of UIC wells that are currently in operation and for which their earthquake potential is unknown. An equal challenge is posed by UIC wells that may be permitted and become active injectors in the future, particularly if the permitting agency for the well is not cognizant of the associated earthquake hazard, or not in communication with parties that would be sensitive to a change in earthquake risk. For example, how close to an existing nuclear power plant or a dam is ``too close`` to site a disposal well permitted for a specified volume and pressure? Whose responsibility is it to evaluate the risk? Who is responsible for notifying the parties at risk? Who carries the liability should a damaging earthquake occur? Getting answers to these questions requires accurately assessing the induced-earthquake hazard, but at present the needed statistics are lacking because of the data gap. The NRC report provides some helpful guidance on how to develop ``best practice`` protocols that could help to close the data gap if implemented The report cites the recently published DOE IS protocol as an important step towards establishing a best practices effort.

The NRC report also found: ``To date, the various agencies have dealt with induced seismic events with different and localized actions. These efforts to respond to potential induced seismic events have been successful but have been ad hoc in nature.`` Above in this testimony, I detailed the large number of induced or potentially induced earthquakes that have occurred in 2011 and 2012. Further, USGS scientists have also documented a seven-fold increase since 2008 in the seismicity of the central U.S., an increase that is largely associated with areas of wastewater disposal from oil, gas and coal-bed methane production. Scientifically, USGS has a depth of expertise relevant to understanding induced seismicity and the increasing demand for better monitoring, analysis, assessment, and public information. We have also worked closely with colleagues in academia and the State Geological Surveys, which have also seen increasing demands.

To meet these increasing demands, we have increased research efforts within our current budget. Looking forward, the Administration has proposed to significantly increase our efforts on induced seismicity in the coming fiscal year, as part of a comprehensive initiative to address potential environmental, health, and safety issues associated with hydraulic fracturing, and we hope that the Congress will support that initiative.

Thank you again for the opportunity to testify and for your attention to this important matter. I would be happy to answer any questions you may have.

Mark D. Zoback, Benjamin M. Page professor, Stanford University, Stanford, Calif.

Committee: Senate Energy and Natural Resources Committee
Subject: Induced Seismicity Potential in Energy Technologies

Testimony:

Statement of Mark D. Zoback, Benjamin M. Page Professor of Earth Sciences and Professor of Geophysics, Stanford University, Stanford, CA

Committee on Senate Energy and Natural Resources

June 19, 2012

Chairman Bingaman, Senator Murkowski and members of the Committee, thank you for asking me to testify today. My name is Mark Zoback, I am a Professor of Geophysics at Stanford University. For your general information, I last spoke to this committee in October as a member of the Secretary of Energy`s Advisory Board Shale Gas Subcommittee. I also served on the National Academy of Engineering committee that investigated the Deepwater Horizon accident. My field of expertise is in quantifying geologic processes in the earth that control earthquakes and hydraulic fracture propagation. I have been doing research in these fields for over 30 years ago. My PhD students and I have been carrying out a number of collaborative research projects seeking to better understand these processes in the context of carbon capture and storage and production from shale gas reservoirs.

While I was not a member of the NRC committee chaired by Professor Hitzman, I did have the opportunity to speak with the committee about the issues I`ll comment upon today. Let me say at the outset that I am in full agreement with the principal findings their report. Today, I will limit my comments to discussing earthquakes and energy technologies in two specific contexts. First, will be earthquakes triggered by injection of wastewater. While wastewater can come from many sources, of particular interest in the past few years has been the injection of the flow-back water coming out of shale gas wells following hydraulic fracturing. Second, I want to comment briefly about the potential for triggered seismicity associated large-scale carbon capture and storage, or CCS, as it is widely known. In most cases, if earthquakes are triggered by fluid injection it is because injecting fluid increases the pore pressure at depth. The increase in pore pressure reduces the frictional resistance to slip on pre-existing faults, allowing elastic energy already stored in the rock to be released in earthquakes. For the cases I will speak about today, the earthquakes in question would have occurred someday as a natural geologic process injection could simply advance their time of occurrence. I have provided the committee staff with recently published papers I`ve written on these topics to provide more details.

Earthquakes associated with wastewater injection

In 2011 the relatively stable interior of the U.S. was struck by a surprising number of small-to-moderate, but widely felt earthquakes. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. The magnitude 5.8 that occurred in northern Virginia on Aug. 23, 2011 that was felt throughout the northeast and damaged the Washington Monument was one of these natural events. While the magnitude of this event was unusual for this part of the world, the Aug. 23rd earthquake occurred in the Central Virginia seismic zone, an area known for many decades to produce relatively frequent small earthquakes. This said, a number of the small-to-moderate earthquakes that occurred in the interior of the U.S. in 2011 appear to be associated with the disposal of wastewater, at least in part related to shale gas production. Following hydraulic fracturing of shale gas wells, the water that was injected during hydraulic fracturing is flowed back out of the well. The amount of water that flows back after fracturing varies from region to region. It`s typical for 2550% of injected water to flow back. While the chemicals that comprise the fracturing fluid are relatively benign, the flow-back water can be contaminated with brine, metals and potentially dangerous chemicals picked up from the shale and must be disposed of properly.

Seismic events associated with injection of wastewater in 2011 include the earthquakes near Guy, Ark., where the largest earthquake was a magnitude-4.7 event on Feb. 27th and the earthquakes that occurred on Christmas Eve and New Year`s Eve near Youngstown, Ohio. The largest Youngstown event was magnitude 4.0. It is understandable that the occurrence of injection- related earthquakes is of concern to the public, government officials and industry alike.

I believe that with proper planning, monitoring and response, the occurrence of small-to-moderate earthquakes associated with fluid injection can be reduced and the risks associated with such events effectively managed. No earthquake triggered by fluid injection has ever caused serious injury or significant damage. Moreover, approximately 140,000 Class II wastewater disposal wells have been operating safely and without incident in the U.S. for many decades.

Five straightforward steps can be taken to reduce the probability of triggering seismicity whenever we inject fluid into the subsurface. First, it is important to avoid injection into faults in brittle rock. While this may seem a ``no-brainer``, there is not always sufficient site characterization prior to approval of a injection site. Second, formations should be selected for injection (and injection rates limited) so as to minimize pore pressure changes. Third, local seismic monitoring arrays should be installed when there is a potential for injection to trigger seismicity. Fourth, protocols should be established in advance to define how operations would be modified if seismicity were to be triggered. And fifth, operators need to be prepared to reduce injection rates or abandon injection wells if triggered seismicity poses any hazard. These five steps provide regulators and operating companies with a framework for reducing the risk associated with triggered earthquakes.

In addition, the re-cycling of flow-back water (for use in subsequent hydraulic fracturing operations) is becoming increasingly common (especially in the northeastern U.S.). This is a very welcome development. Re-use of flow-back water avoids potential problems associated with transport and injection flow- back water or the expense and difficulty of extensive water treatment operations. It is important to note that the extremely small microseismic events occur during hydraulic fracturing operations. These microseismic events affect a very small volume of rock and release, on average, about the same amount of energy as a gallon of milk falling off a kitchen counter. The reason these events are so small is that pressurization during hydraulic fracturing affects only limited volumes of rock (typically several hundred meters in extent) and pressurization typically lasts only a few hours. A few very small earthquakes have occurred during hydraulic fracturing (such as a magnitude-2.3 earthquake near Blackpool, England, in April 2011), but such events are extremely rare.

It is important for the public to recognize that the risks posed by injection of wastewater are extremely low. In addition, the risks can be minimized further through proper study and planning prior to injection, careful monitoring in areas where there is a possibility that seismicity might be triggered, and operators and regulators taking a proactive response if triggered seismicity was to occur.

Earthquake potential and large-scale carbon storage

I would now like to comment briefly about the potential for triggered seismicity associated large-scale carbon capture and storage. My colleague Steve Gorelick and I have recently pointed out that not only would large-scale CCS be an extremely costly endeavor, there is a high probability that earthquakes will be triggered by injection of the enormous volumes CO_2 associated with large-scale CCS.

There are two issues I wish to emphasize in particular this morning.

First, our principal concern is not the probability of triggering large earthquakes. Large faults are required to produce large earthquakes. We assume that such faults would be detected, and thus avoided, by careful site characterization studies. Our concern is that even small-to-moderate size earthquakes would threaten the seal integrity of the formations being used to store CO_2 for long periods without leakage. Studies by other scientists have shown that a leak rate from underground CO_2 storage reservoirs of less than 1% per thousand years is required for CCS to achieve the same climate benefits as switching to renewable energy sources.

Second, it is important to emphasize that we recognize that CCS can be a valuable and useful tool for reducing greenhouse gas emissions in specific situations. Our concern is whether CCS can be a viable strategy for achieving appreciable global greenhouse gas reductions. From a global perspective, if large-scale CCS is to significantly contribute to reducing the accumulation of greenhouse gases, it must operate at a massive scale, on the order of 3.5 billion tonnes of CO_2 per year. This corresponds to a volume roughly equivalent to the 27 billion barrels of oil currently produced annually around the world.

Multiple lines of evidence indicate that pre-existing faults found in brittle rocks almost everywhere in the earth`s crust are close to frictional failure, often in response to small increases in pore pressure. In fact, over time-periods of just a few decades, modern seismic networks have shown that earthquakes occur nearly everywhere in continental interiors. In light of the risk posed to a CO_2 repository by even small-to-moderate size earthquakes, formations suitable for large-scale injection of CO_2 must be well-sealed by impermeable overlaying strata, weakly cemented (so as not to fail through brittle faulting) and porous, permeable, and laterally extensive to accommodate large volumes of CO_2 with minimal pressure increases.

Thus, the issue is not whether CO_2 can be safely stored at a given site, the issue is whether the capacity exists for sufficient volumes of CO_2 to be stored in geologic formations for it to have a beneficial affect on climate change. In this context, it must be recognized that large scale CCS will be an extremely expensive and risky strategy for achieving significant reductions in greenhouse gas emissions.

Mr. Chairman, Senator Murkowski and members of the Committee, thank you for the opportunity to speak to you today.